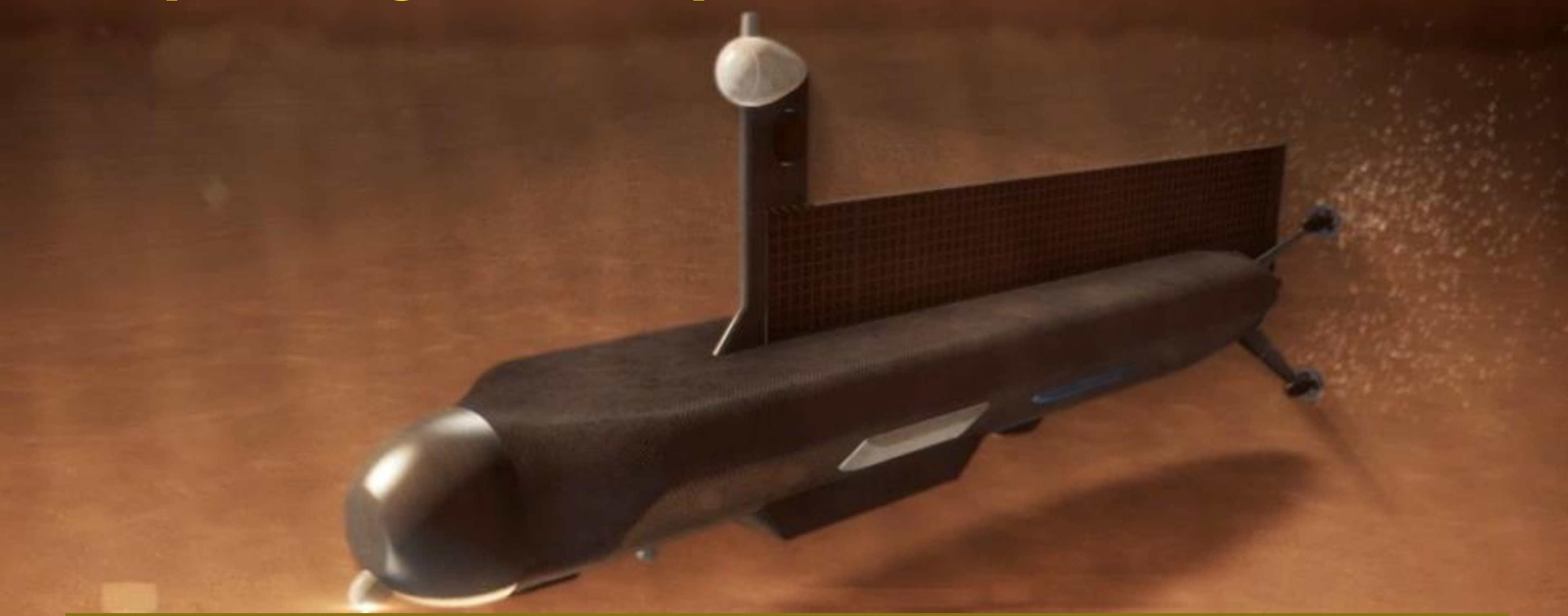
Titan Submarine:

Exploring the Depths of Kraken Mare



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26th Space Cryogenic Workshop
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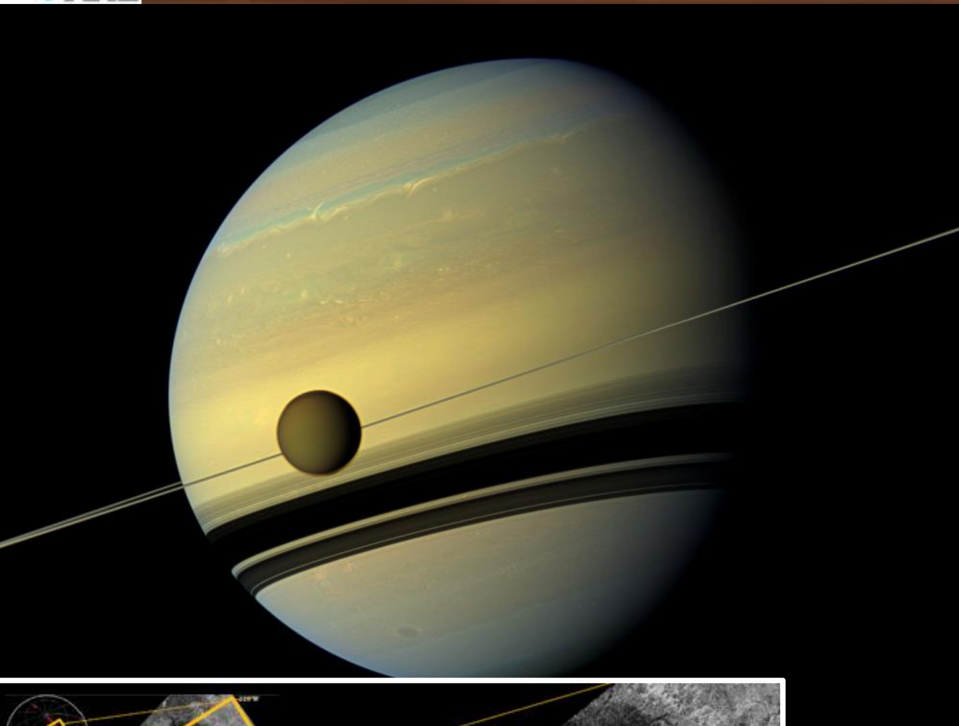
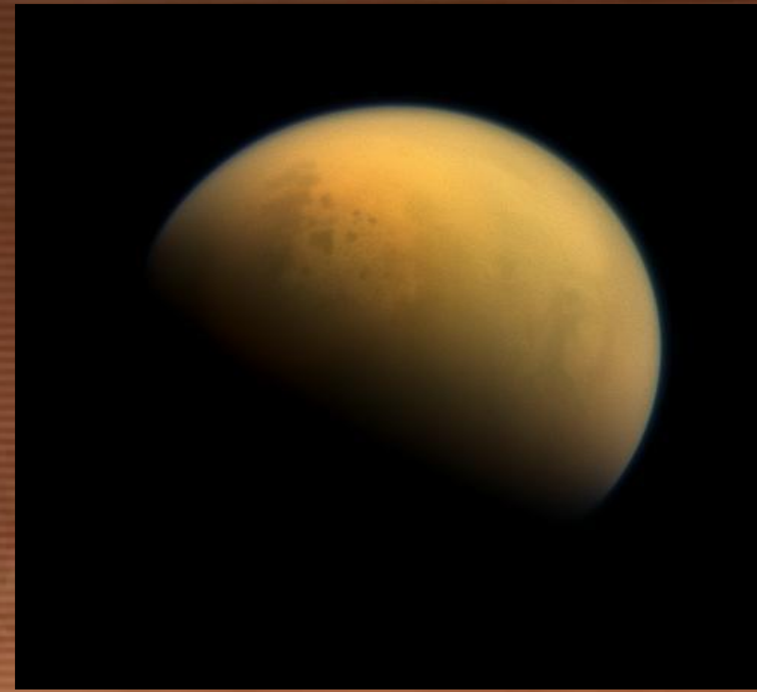
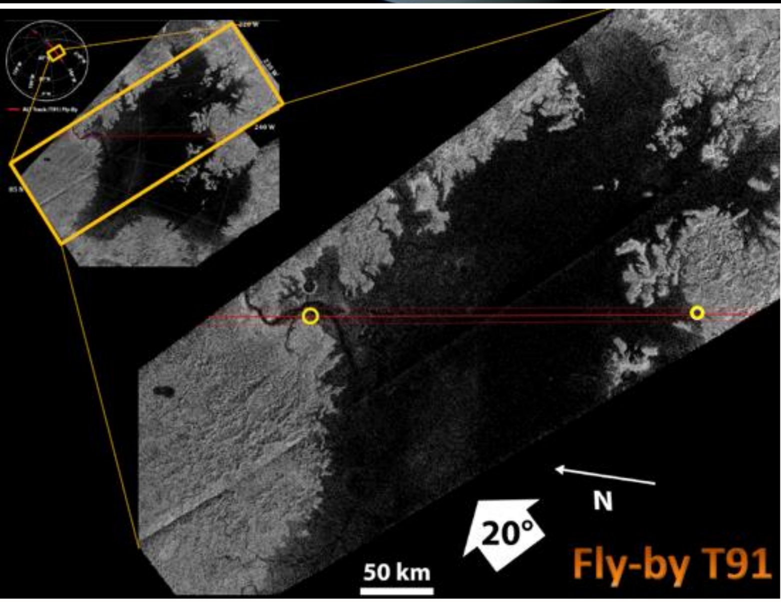
Executive Summary







- We designed a submarine to go to Titan – NIAC Phase I
- Goal of NIAC – “enable exciting, unexplored, credible aerospace concepts with at least one mission application that addresses NASA goals”
- High level concept design/trade study
- Direct mission, 1 year exploration of Titan seas
- Fully instrumented, autonomous, unique submersible design for operation in cryogenic liquid hydrocarbons
- Focus on: Titan, Submarine, Trades on power, thermal, and buoyancy control

Saturn Titan Cryogenic Environment

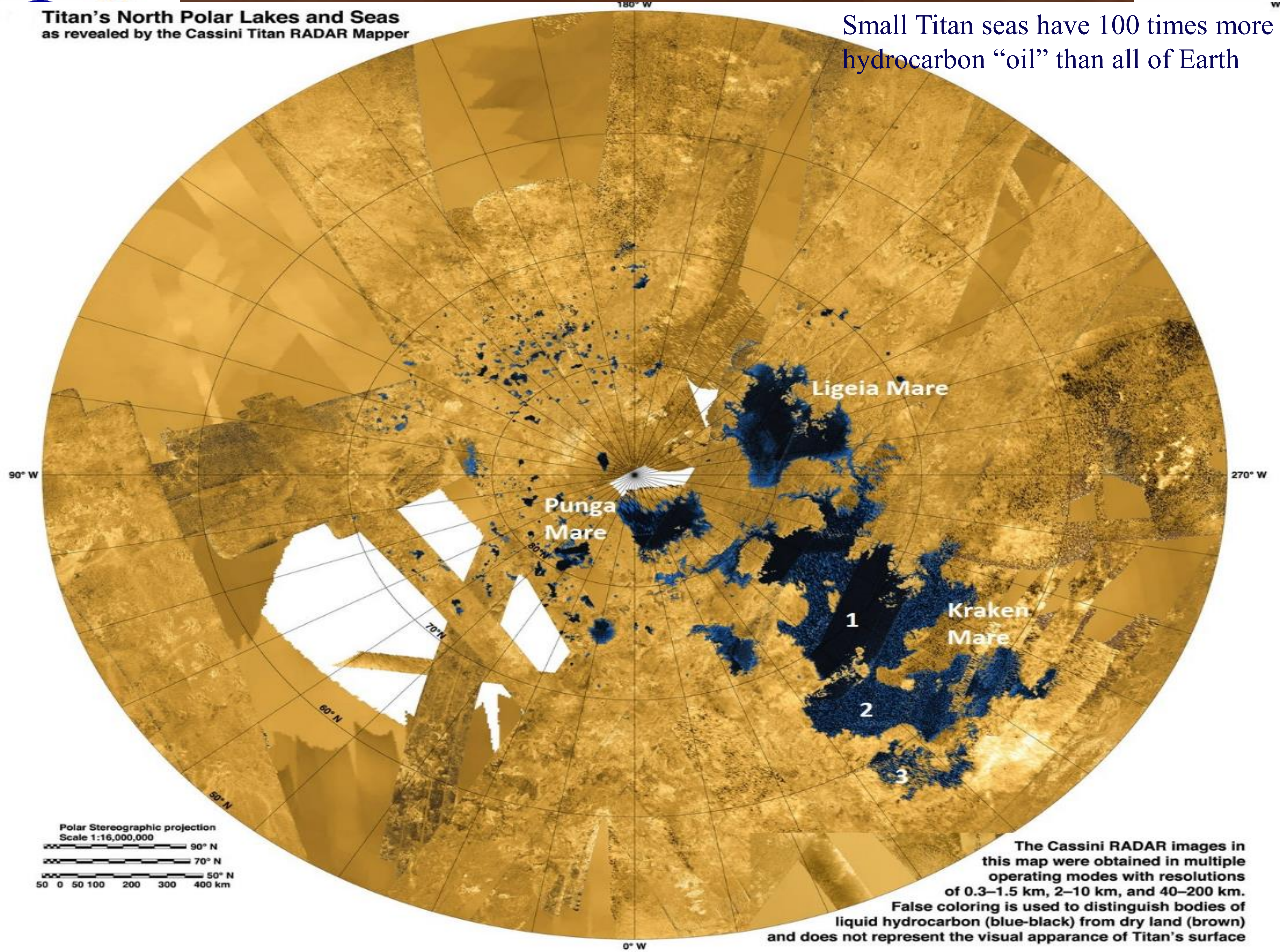
1. Titan is the only known body (other than Earth) within Solar System with stable seas
   - Stable hydrocarbon seas similar in size/depth as Great Lakes on Earth
   - 3 seas have been mapped by Voyager & Cassini - Punga, Kraken, and Ligeia Mare, all in north polar region, all of differing ethane/methane/nitrogen compositions

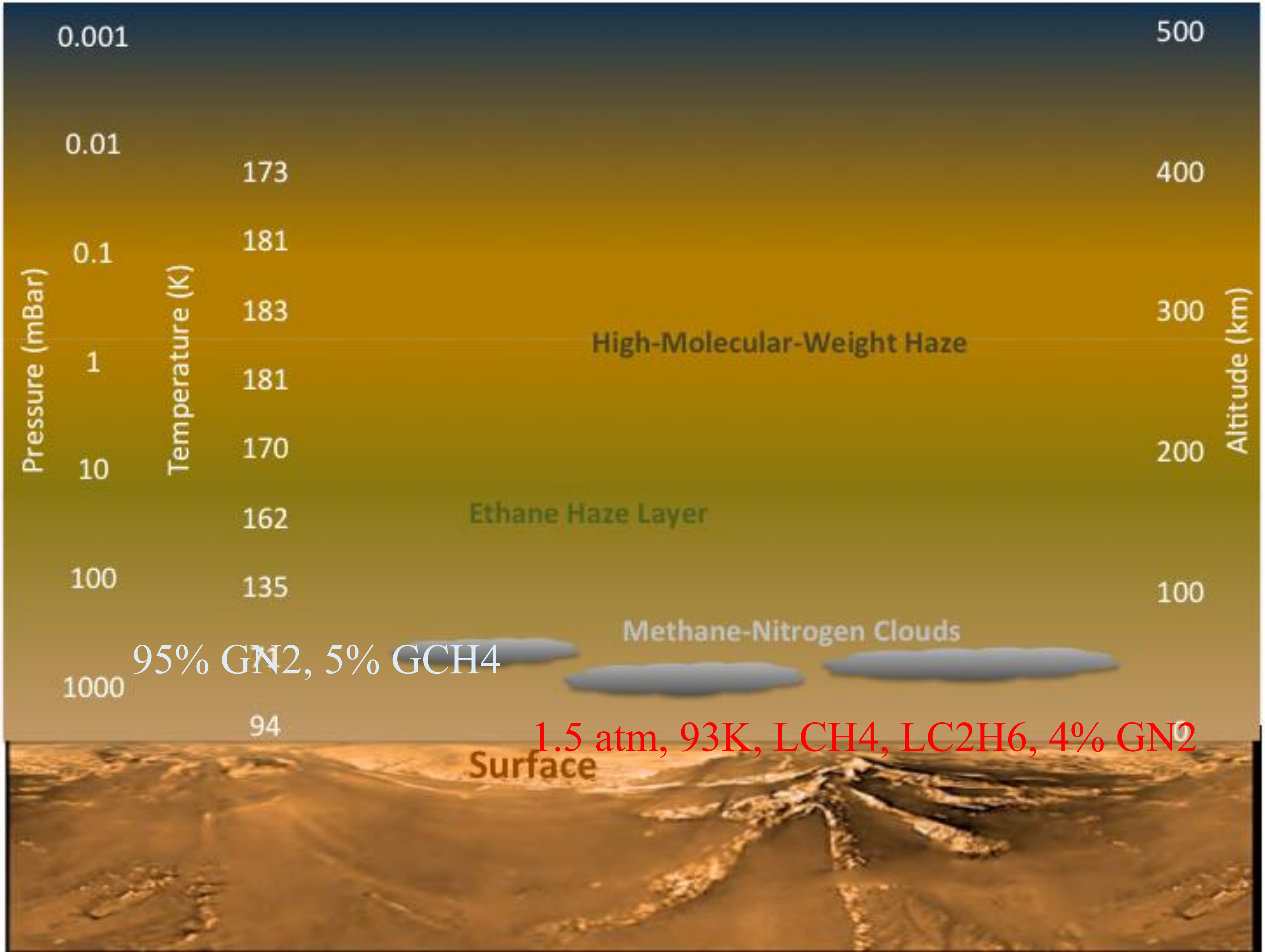
   - Liquid surface temperature 90-96K; near freezing point of ethane and methane
   - Seas ~96% Liquid (ethane or methane), 4% GN2
   - Density variations of 30%

2. Only known moon with significant atmosphere (early Earth)
   - Organic compounds accumulate to form thick haze, clouds
   - 1.5 atm, 95% GN2, 5% GCH4
   - 5x density of Earth
   - 14% Earth gravity

- Titan is the 2nd-largest planetary satellite (5150km diameter) in Milky Way (Ganymede 5276 km)

Small Titan seas have 100 times more hydrocarbon “oil” than all of Earth





0.001
0.01
0.1
1
10
100
1000
Pressure (mBar)
Temperature (K)
173
181
183
181
170
162
135
94
500
400
300
200
100
0
Altitude (km)
High-Molecular-Weight Haze
Ethane Haze Layer
Methane-Nitrogen Clouds
95% GN2, 5% GCH4
1.5 atm, 93K, LCH4, LC2H6, 4% GN2
Surface

Mission Timeline

2038

Launch

Trans-Titan Insertion

Interplanetary Cruise

~7 Years

Titan Atmospheric Entry & Descent

~2.5 hours

Kraken Mare Splashdown

Sub Activation & Checkout — **~4 days**

First Transit — **~7 days**

Map and Explore Kraken-1 — **~90 days**

Map and Explore Kraken-2 — **~90 Days**

Return to Ligeia Mare and enter if possible — **~120 Days**

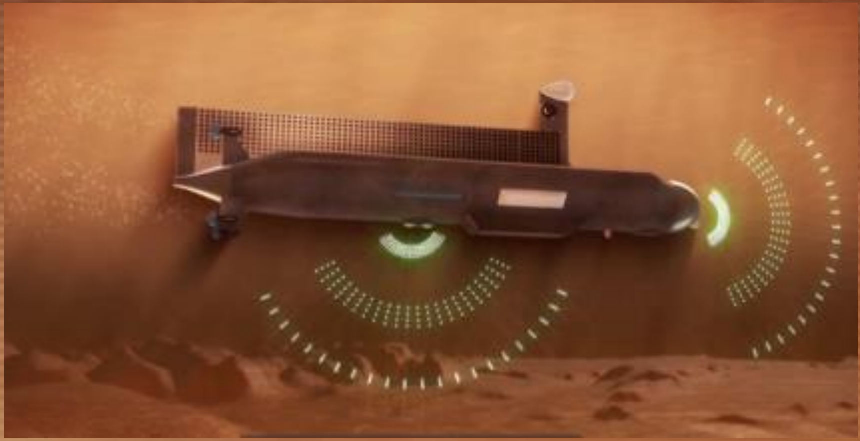
End Of Primary Mission

Cruise Day:

- ***8 hrs Submerged Science/Transit***
- ***16 hrs Surfaced shore imaging/meterology/data return***

Phase I Submarine Design Approach

- Design driven by science
  - Traceability to Decadal Survey
  - Astrobiology: Evolution of hydrocarbons in universe
  - Geology: atmosphere/sea exchange, surface, shore, waves, heat transfer



<u>High Level System Requirements</u>

- Operation in cryogenic sea (93K)
- Autonomous
- Max Speed: 1 m/s
- Range: ~ 3000 km / 1 year
- DTE communication (remove need for orbiter)
- Submerged durations: 8 hours
- Surfaced Communications duration: 16 hours
- Depth: up to 1 km
  - Pressurize sub to ~150psi
- 5-g axial loads, 2-g lateral loads

Why a submarine? Provides more efficient, in-situ science system that is very long range and very maneuverable (similar to earth's AUVs).

To study atmosphere/sea exchange processes, vehicle should look like this:

To maneuver near and interact with/sample the seabed, vehicle should look like this:

To traverse large distances at speed using limited energy, vehicle should look like this:

To send back lots of data, your vehicle should look like this

For launch, cruise, and hypersonic entry, your vehicle should perhaps look like this:

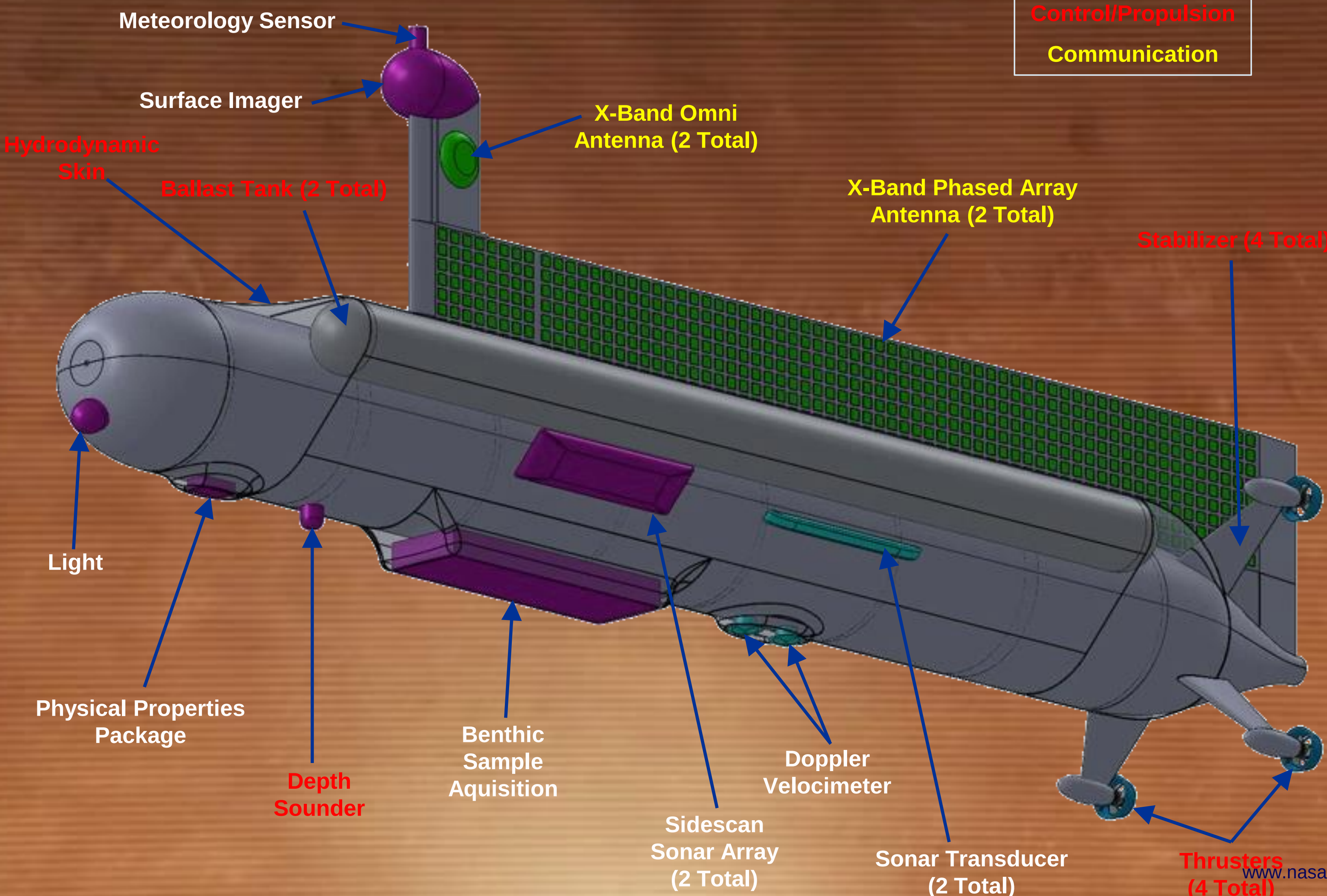
Titan Submarine

- Cylinder shapes more efficient for transit
- 1200 kg submarine
- 6m long x 1.1m wide x 2m high

Science

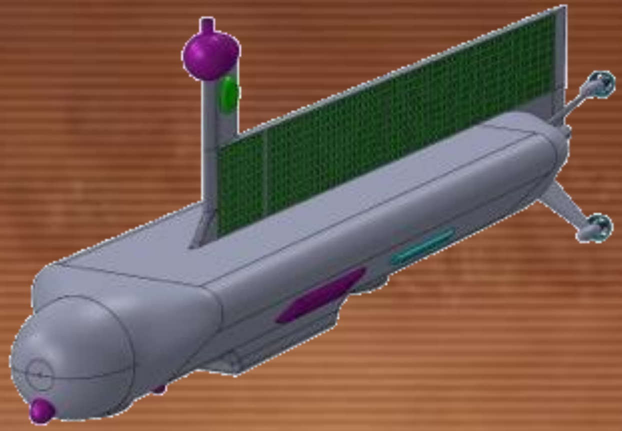
Control/Propulsion

Communication



Phase I Design Trades

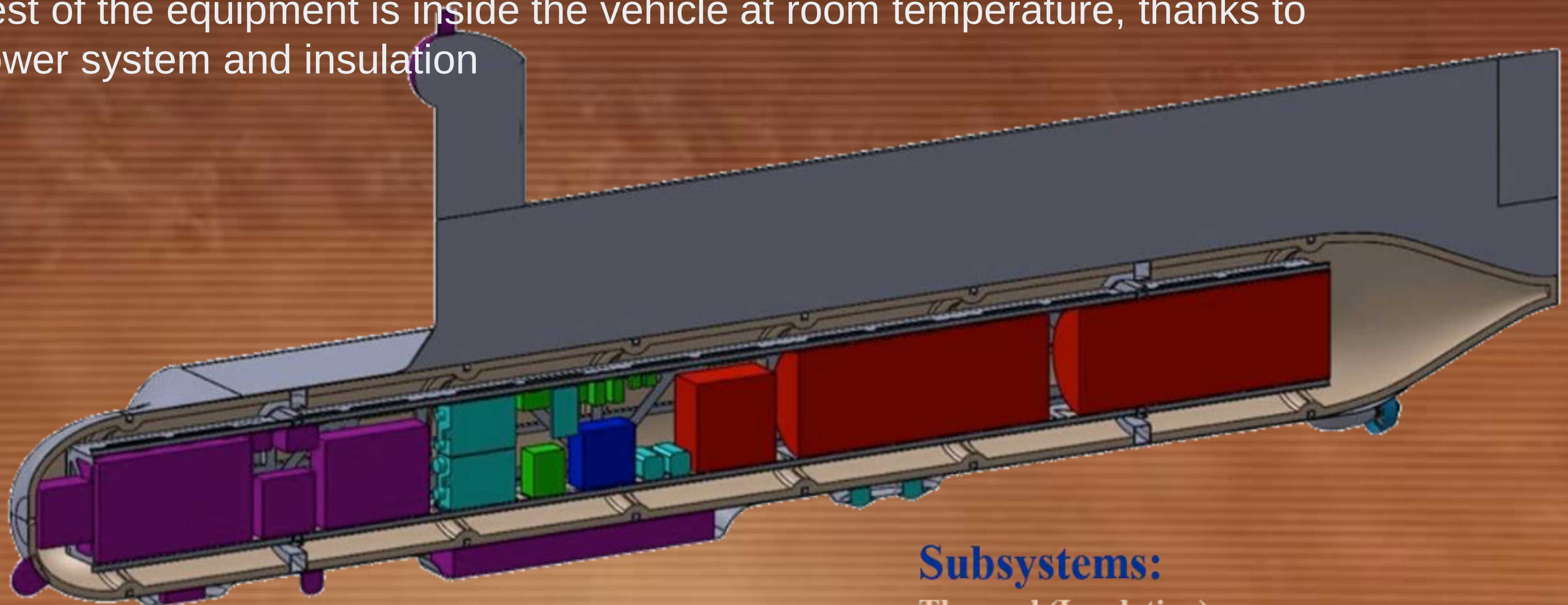
- Navigation
- Command/Data
- Communication
- Steering
- Configuration



- Aeroshell Selection
- Propulsion
- Science
- Power
  - Isotope
  - Fission
  - Methane
    - Fuel Cell
- Buoyancy
  - Ballast tanks
  - Compressed Gas, Pumps
  - Heat exchanger to boil methane and blow tanks
- Thermal
  - Isotope or fission waste heat
  - Low temp components
- Structure

Cryogenic Equipment

- All external equipment will need to endure, operate, and cycle at low (93K) temperatures
  - Propulsive Motors
  - Communications phased array
  - Ballast system (compressors, valves, pistons, etc.)
  - Science
- The rest of the equipment is inside the vehicle at room temperature, thanks to the power system and insulation



Subsystems:
Thermal (Insulation)
Attitude Determination and Control
Command and Data Handling
Communications
Electrical Power
Science
Structures

Power – Requirements & Specs

Power Mode 1	Power Mode 2	Power Mode 3	Power Mode 4	Power Mode 5	Power Mode 6	Power Mode 7	Power Mode 8	Power Mode 9	Power Mode 10
(W)	(W)	(W)	(W)	(W)	(W)	(W)	(W)	(W)	(W)
Launch	Interplanetary Cruise	Titan EDL	Sub Activation & Checkout	Dive/Surface	Submerged Cruise	Surface Cruise	Stationary Submerged Operations	Stationary Surface Operations	End of Mission Disposal
60 minutes	TBD Years	2 hours	1 week	TBD minutes	TBD days	TBD days	TBD days	TBD days	0.0
78	91	117	842	826	839	746	269	534	166

Options

1. Fission — too heavy @ 400 kg
2. Fuel cells (LO2/in-situ LC2H6, need about 2 kg/day) — too heavy @ 700 kg
3. Multi-mission radioisotope generators — high Pt use, low specific power, high degradation, 275 kg
4. Stirling Radioisotope Generators (SRGs)

- high power density
- long life, low power degradation
- proven flight heritage
- 2x500W
- 200 kg
- 3800W waste heat to be removed

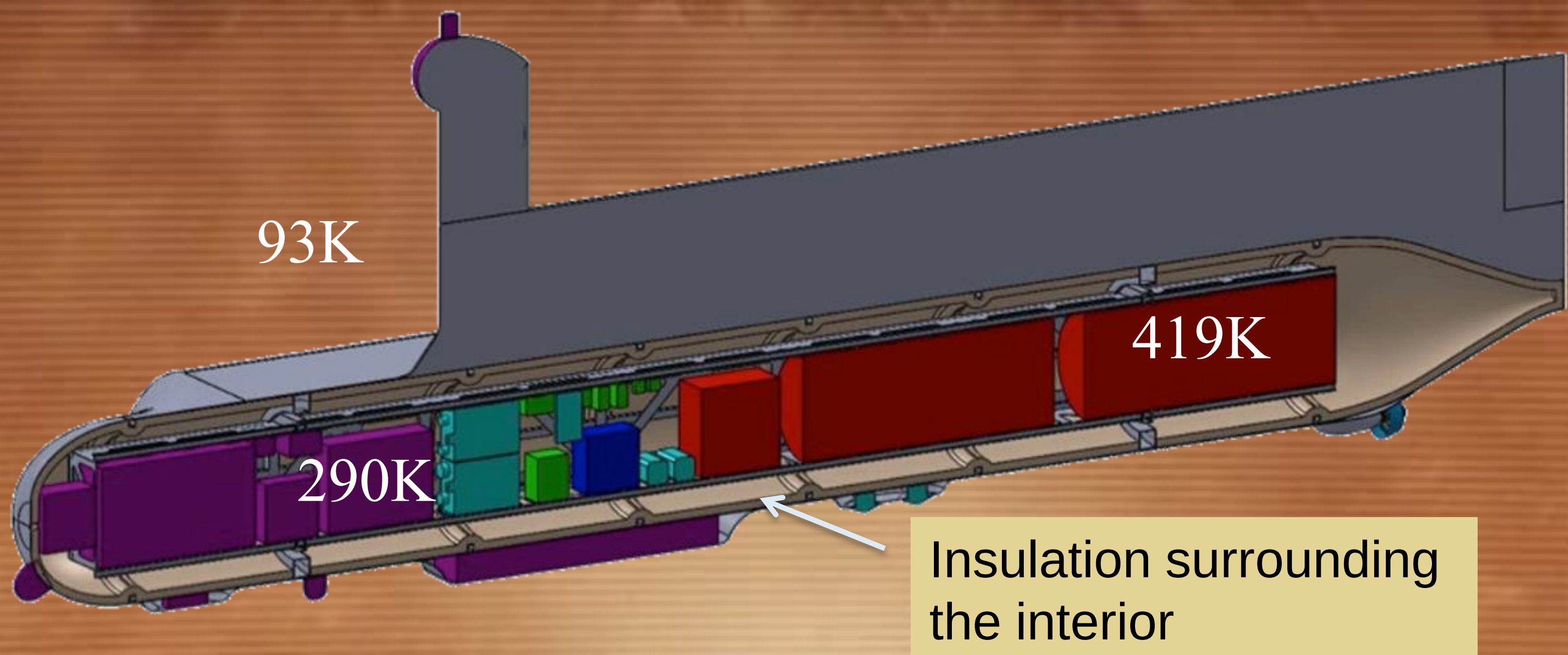
Simplified thermal management in cryogenic Titan seas – excess waste heat available to maintain warm ambient temperatures for internal components

Thermal – Approach

Prime Requirement: Maintain the submarine interior at around 290 K while operating within the seas.

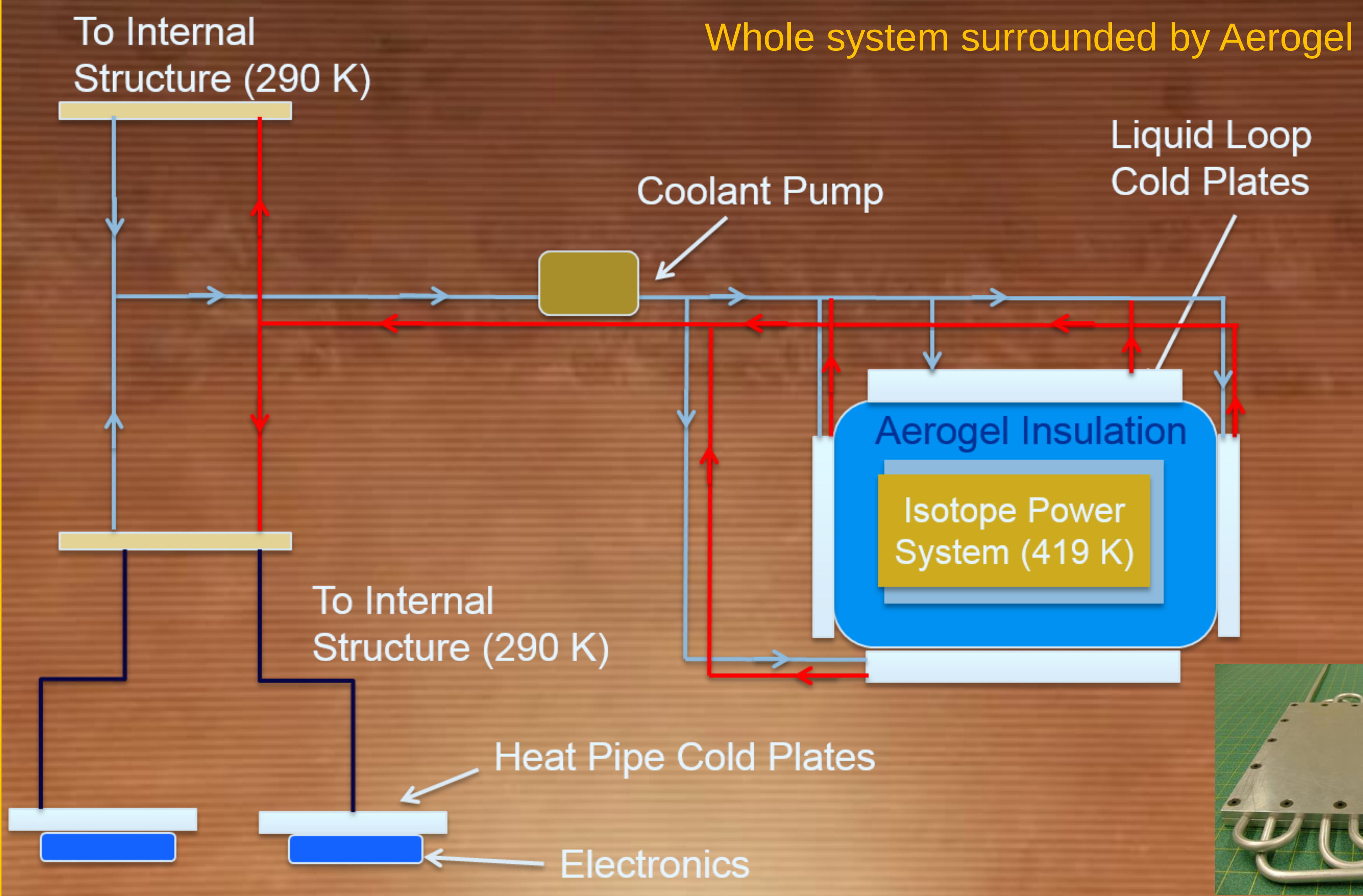
Thermal System Approach:
The thermal system is based on a thermal balance between the heat generated by the SRGs heat used to provide power, and the heat loss to the surroundings through the submarine exterior. This is accomplished by distributing the waste heat from the isotope system throughout the interior, and insulation to obtain the correct temperature difference between the interior and exterior of the vehicle

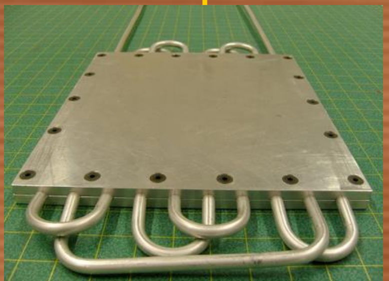
- A pump loop coolant system to move the heat from the isotope system and distribute it within the interior.
- Cold plates and heat pipes to move the heat from the electronic sources to the interior
- Insulation covering the interior of the submarine



Thermal – Operation in Titan Seas

Excess Heat is moved from the isotope system to the internal structure which distributes the heat throughout the interior of the submarine





Thermal – Sizing Insulation Thickness

Heat cannot accumulate inside sub. Balance waste heat from SRGs (interior) to exterior

Interior

$$\dot{Q}_{SRG} = \dot{Q}_i + \dot{Q}_w + \dot{Q}_{vp} + \dot{Q}_{cl} + \dot{Q}_{ss} = \dot{Q}_c$$

$$\dot{Q}_i = \frac{k_i A_i \left(T_i - T_s\right)}{t_i}$$

Ti, Ts, appear in each conduction term, therefore need to iterate

$\dot{Q}$ through wires, view ports, coolant loop, supports

$$\left.\begin{aligned} T_i &= \text{internal temp} \\ T_s &= \text{external sub temp} \\ t_i &= \text{insulation thickness} \end{aligned}\right\} \textit{Unknowns}$$

Exterior

$$\dot{Q}_c = A_s h\left(T_s - T_{sea}\right) \text{ where } h = \frac{Nuk_{sea}}{L_s}$$

Solution

1. *Guess ti*
2. *Choose appropriate Ti*
3. *Solve for Ts*
4. *Check Energy balance*
5. *Iterate until heat input = heat output*

Moving

$$Nu = 0.3 + \frac{0.62\,\mathrm{Re}^{1/2}\,\mathrm{Pr}^{1/3}}{\left[1+\left(\frac{0.4}{\mathrm{Pr}}\right)^{2/3}\right]^{1/4}}\left[1+\left(\frac{\mathrm{Re}}{2.82x10^5}\right)^{5/8}\right]^{4/5}$$

Quiescent

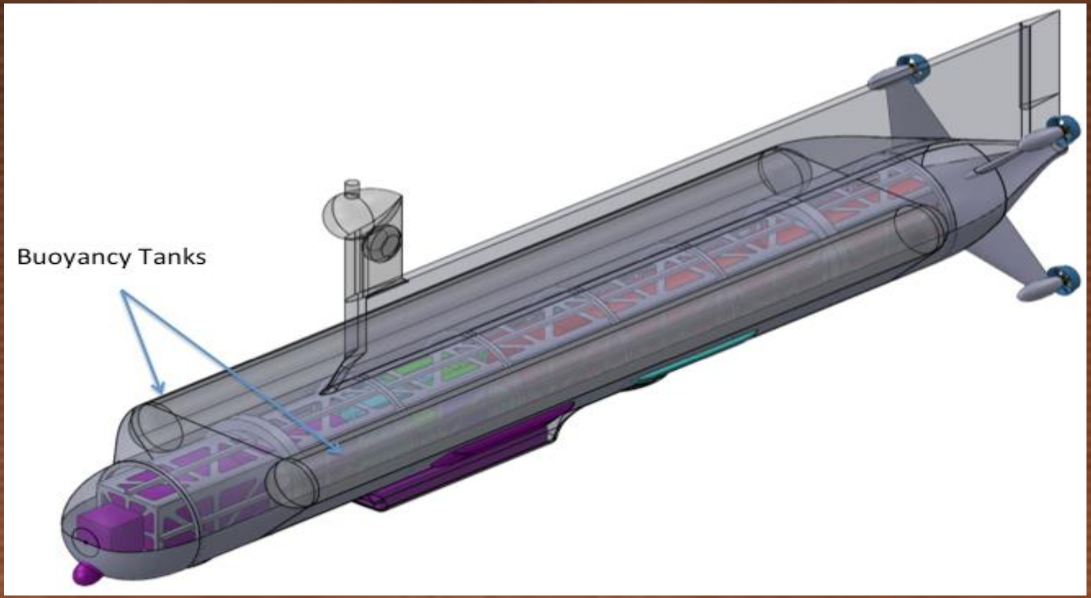
$$Nu = \left[0.6 + \frac{0.387\,Ra^{1/6}}{\left[1+\left(\frac{0.559}{\mathrm{Pr}}\right)^{9/16}\right]^{8/27}}\right]^2$$

Thermal – Specs

Specifications	Value
Isotope System	Heat rejection temperature of 419 K
Waste heat Provided by the isotope power system.	3800 W
Operating Temperature	Internal ~ 290 K to 310 K (17 °C to 37°C)
Insulation (aerogel foam) 	3.0 cm thick k = 0.028 W/mK, $\rho = 20\ kg/m^3$
External Skin Temperature	94 K

Small ΔT between external skin and sea, minimizes likelihood of boiling or bubbling

Buoyancy System Trades



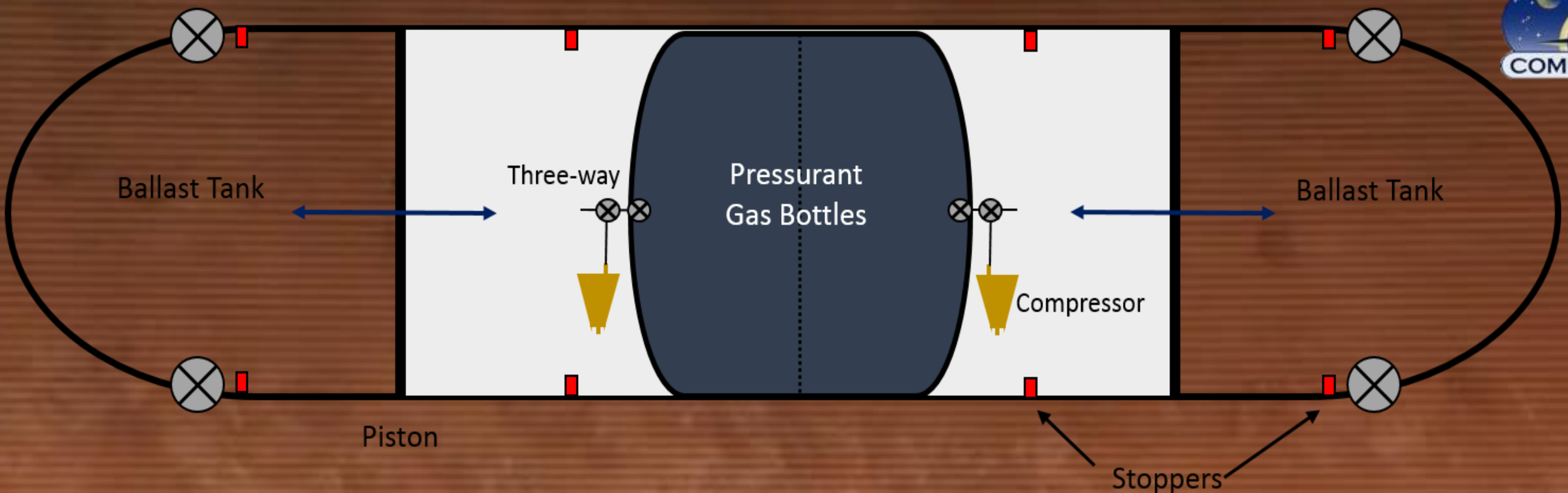
Ascent

Descent

Hovering

1. Dive planes and power
   - Craft would only stay submerged when moving
2. Vacuum tank to pump Titan sea liquid out of ballast tanks
   - Too heavy
3. Reverse ballast approach using compressors and coolers
   - Too heavy
4. Boil the liquid to provide buoyancy
   - Complicates thermal management and pressure control due to phase change
   - Insufficient waste heat to boil required amount of liquid methane/ethane
5. GN2 or LN2 ballast tanks
6. GNe ballast tanks

Ballast Tank



Condensable (GN2) vs. Non-condensable (GNe)

Concerns common for both systems

1. Need for compressors - recover and store pressurant for ascent stage
2. Need for mechanical separation between liquid ethane/pressurant gas L/V interface
   - GN2: pressure control complicated due to gas dissolving, condensation, and evaporation
   - GNe: possible gas dissolving; need to fully recover pure gas (better predictability for autonomous control)
3. Need for cryogenic rated compressors, valves, etc.
4. Leakage rate (worse at cryo temps)
5. GN2 solubility (worse at cryo temps)

$$\vec{V} \propto \sqrt{\frac{m}{T}}$$

Gas Side of Ballast Tank

Condensable (GN2) vs. Non-condensable (GNe)

Concerns exclusive to GN2

1. Difficulty in pressure control due to phase change

   - During ascent, gas would be pressurized to a pressure above the saturation pressure, where condensation can occur; descent, evaporation

2. Compressibility issue

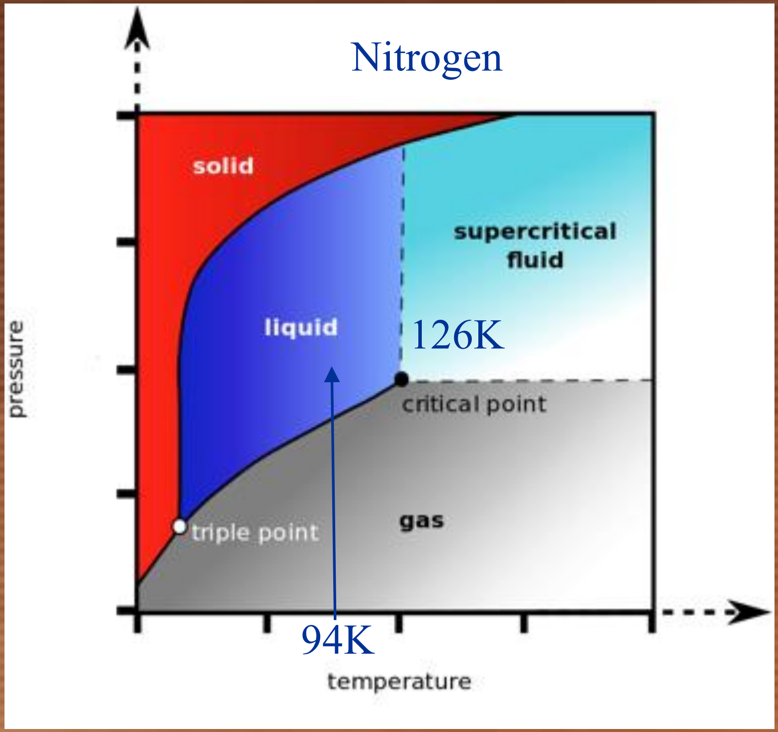
   - Have to heat gas and maintain $T_{gas} > T_{ambient}$ for all phases of mission

   - Greater insulation thickness

   - Pressurant gas bottle has to be located inside main vehicle

3. Solubility

- Could consider using LN2 as a pressurant, but phase change during expulsion stage is inevitable, and harder to control pressure with incompressible



- Cannot isothermally compress gas

Gas Side of Ballast Tank

Condensable (GN2) vs. Non-condensable (GNe)

Concerns exclusive to GNe

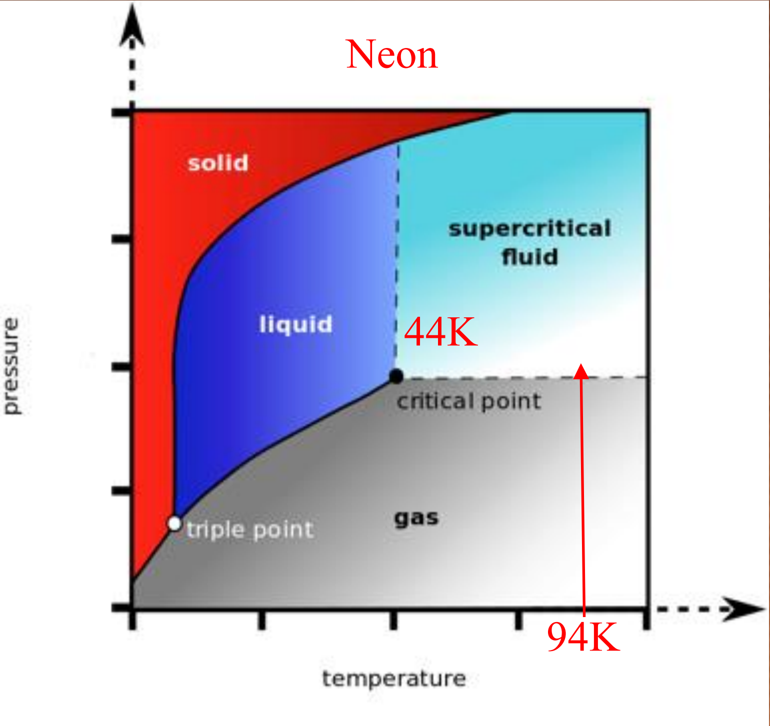
1. Gradual leakage across mechanical interface; inability to recover lost gas

Ballast Tank

- Liquid volume displaced per ballast tank 0.229 m^3
- L ~ 4 m , D = 0.27 m
- Use of piston as mechanical divider. (could use bellows)

Pressurant Gas Tank

- Baseline Gaseous Neon as pressurant gas
- Titanium tank (no material compatibility issues)
- 1000 psia storage pressure



- Assume isothermal pressurant tank blowdown (function of ascent rate)
- Required pressurant gas m = 6.25 kg
- For 16 hours at surface, required pump power < 20W

- *Can* isothermally compress gas

Stay tuned for Phase 2!

Summary

1. Power – SRGs
2. Thermal – Liquid Cold Plates, Heat Pipes, Aerogel
3. Buoyancy – Gaseous Neon/Ballast Tanks

- Submarine design meets all science and mission requirements

Future work

1. Titan sea properties
2. Detailed thermal model of ballast tanks – feasibility of using GN2

For more information:

Phase I NIAC Final Report

YouTube Video

Dozens of science articles

Upcoming special on BBC

Stay tuned for Phase II